Research article

The importance of pH and sand substrate in the revegetation of saline non-waterlogged peat fields

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ABSTRACT

A partially peat-extracted coastal bog contaminated by seawater was barren and required revegetation as a wetland. Peat fields were rectangular in shape, cambered in cross-section profile, and separated by drainage ditches. Common to all peat fields were symmetrical patterns in micro-topography with slopes between differences in elevation. Saline non-waterlogged slopes of ~5% occurred as a symmetrical pair on each side of the crest of the cambered profile, at one end of each peat field. Three rows were laid across this slope (Top, Middle, and Bottom rows) and transplanted with naturally-growing plant species with their sand substrate, in three experiments, and grown for a year. In the *Spartina pectinata* experiment, bare root stem sections were also planted. Another experiment was conducted to determine changes in the characteristics of a volume of sand when incubated in saline peat fields. We found the salinity of peat increased with moisture downslope, and pH decreased with increase in salinity. *S. pectinata* grew best when planted with its sand substrate compared with bare root stem section, and when planted in Bottom rows. *Juncus balticus* had excellent growth in all rows. Unexpectedly, *Festuca rubra* that was inconspicuous beneath the *J. balticus* canopy in the natural donor site grew densely within the *J. balticus* sods. *Agrostis stolonifera* grew well but seemed to show intolerance to the surrounding acidic peat by curling up its stolons. The pH of the incubated sand volume was much higher than the surrounding peat. These studies suggest that recognition of plant niches and pH manipulation are important in the revegetation of disturbed *Sphagnum* peatlands that are found abundantly in the northern hemisphere. Results are also relevant to the reclamation of other disturbed lands.

1. Introduction

Transplantation of wild plants as sods with their natural substrate or soil intact is one of several techniques used to revegetate a wetland site, and is known to increase plant establishment success in part due to the presence of beneficial root microorganisms (Hoag, 2003). An experiment by Thomsen et al. (2005) found that after 9 months of growth, the biomass of transplants using natural stock was greater than those of nursery stock. Steed and DeWald (2003) collected sods of wild sedges using soil core samplers of two sizes: 5 cm diameter × 15 cm deep (295 cm³), and 7.6 cm × 15 cm deep (680 cm³), to revegetate riparian meadows and found significantly higher survival and growth from the larger sod. Fraser and Kindscher (2001) successfully used a 60 cm diameter tree spade to collect sods of *Spartina pectinata* and *Eleocharis macrostchya* (Britt.) from a natural wetland for transplant to a wetland restoration site. Transplanting is appropriate for plants that are clonal or reproduce poorly by seed (Fraser and Kindscher, 2001). On a much larger scale, mats of wild vegetation two to six square meters with up to 70 cm of soil attached have been stripped and relocated to restoration sites (Ross et al., 2000). This direct transfer technique has been used to restore native grasslands, wetlands, scrubland, and forests. The direct transfer technique is accomplished through the use of various earth-moving machinery; operator skill and scheduling are critical.

The revegetation of a partially peat-extracted and drained peatland is a challenge particularly when it is contaminated with salt (Montemayor et al., 2008, 2010). Salinity precludes the reestablishment of the original freshwater peatland species but the site can potentially be revegetated and reclaimed into another type of a self-sustaining wetland. The salt marsh as a template for topographical and spatial distribution pattern of plant species, and a

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source of donor vegetation seems obvious. However, the acidity of the peat would likely preclude the survival of many of the salt marsh species which are adapted to neutral (pH 7.0) or near neutral conditions; for example pH 6—7.5 (Portnoy and Giblin, 1997), pH 7.1 (Benner et al., 1985) and pH 6.8 (Compeau and Bartha, 1984).

Soil pH is an important factor affecting the distribution of native plant species (e.g. Steele, 1955; Marrs and Bannister, 1978; Goldberg, 1982). The growth limiting factor of very acid soils include inhibition to root growth or hydrogen ion injury to roots (Islam et al., 1980), hydrogen ion (H^+) toxicity, aluminum (Al^{3+}) toxicity (mineral soils), manganese toxicity (Foy, 1984), and decrease in the uptake and solubility of important nutrients and minerals for plant growth (Marschner, 1991). There are two types of soil acidity — mineral soils which are naturally buffered by aluminum, and organic soils (e.g. peat) in which aluminum is naturally not present (Proctor, 1999; Kidd and Proctor, 2001). While our previous study (Montemayor et al., 2008) did not specifically test plant species or species populations for H^+ tolerance, these cited works indicate that such a type of plant adaptation can be an important consideration in the selection of plants for revegetation of peatlands. A common practice in acidic mineral soils is to apply a substance (e.g. lime) that would increase pH to suit at least the minimum pH requirement of plants.

Daigle et al. (1993) recommended the application of a thin layer of sand on peat fields to provide nutrients as part of an overall restoration plan for the Pokesudie Bog after closure of production. Following this recommendation, an experiment of spreading a thin layer of sand on the surface of barren saline and waterlogged areas of peat fields was tested and plots were transplanted with *Juncus balticus* (personal observation). The effect of sand could not be discerned from the adverse effect of waterlogging on *J. balticus*; this species was subsequently found to be intolerant to prolonged waterlogging (Montemayor et al., 2008).

The purpose of the set of studies reported in this current paper was to test the suitability of *Spartina pectinata*, *J. balticus* and *Agrostis stolonifera* with their natural sand substrate, to revegetate the saline non-waterlogged areas of a barren, partially peat-extracted, and seawater contaminated peat fields. The selection of *S. pectinata* and *J. balticus* was based on their excellent and fair survival, respectively, in our previous study (Montemayor et al., 2008). *A. stolonifera* was selected based on its presence near the study area and its known partial tolerance to salinity and flooding (Rozema and Blom, 1977; Wu, 1981). The specific objective of these experiments was to determine the survival and growth of *J. balticus*, and *A. stolonifera* when transplanted with their natural sandy substrate intact, and *S. pectinata* when transplanted with its natural sandy substrate intact, and as bare root stem sections. In addition, we wanted to determine changes in pH, electrical conductivity (salinity), and moisture content of a volume of non-saline sandy soil incubated in saline peat fields that would likely provide some explanation to the responses of transplanted species.

2. Study area and methods

2.1. The study area

The study area is located on Pokesudie Island, in the Bay de Chaleur, New Brunswick, Canada (47°49N, 64°45′W). The area requiring revegetation was the northern portion of the partially extracted bog (a total area of 150 ha) closest to the sea (~500 m) that was contaminated by seawater (a total of 22 ha) during a storm surge in January 2000. The area was originally an ombrogenous bog composed predominantly of *Sphagnum* peat with some intervening layers of sedge peat, overlying wood peat and ultimately, a sand substrate; the bedrock consists of sandstone (Rampton et al., 1984).

Sand, a readily available material (DNRE, no date) was used to construct the service road and the yard of the peat processing plant. Several terrestrial and some salt marsh species have colonized as ruderals on these non-saline sandy areas and were plant sources for use in the revegetation of peat fields. Undisturbed bogs border the study area on the east and west sides, and salt marshes on the north side. Nearby salt marshes were sources of plant materials, previously demonstrated by Montemayor et al. (2008).

The revegetation area is the same as described by Montemayor et al. (2008) and Mouneimne and Price (2007). It consisted of parallel rectangular (30 m wide, 300—400 m long) peat fields oriented in approximately north-south direction. The middle cross sections of peat fields were of the lowest elevation which rose gradually towards both ends of each peat field. The highest elevated area by the service road, on the south end of peat fields was not affected by salinity (Mouneimne and Price, 2007). The microtopography of each peat field offered several niches or types of micro-sites for revegetation depending on the spatial patterns of moisture with salinity. Five types of saline micro-sites common to all peat fields were identified (Fig. 1): a) dry — elevated longitudinal areas formed by the crests of the cambered profile (Fig. 1 inset); b)
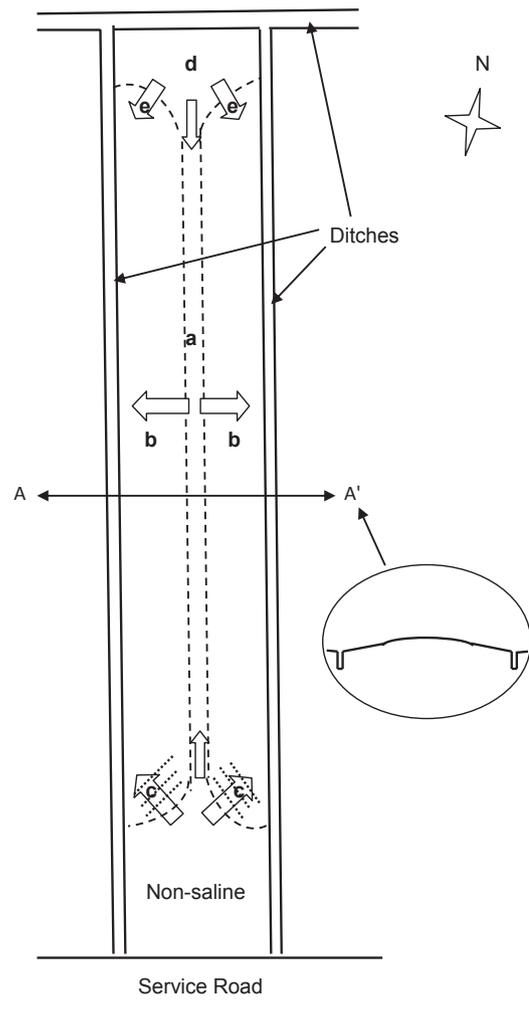
Fig. 1. Schematic diagram of a peat field showing the five saline micro-sites: a) dry, b) waterlogged, c) non-waterlogged with non-saline upslope, d) very dry, and e) non-waterlogged with saline upslope. Slopes are indicated by wide arrows. Micro-sites b) and c) were used in this current study. The inset is the field profile across micro-sites a) and b) and adjacent ditches. Drawing is not to scale.

waterlogged − a pair of longitudinal waterlogged areas located on opposite sides of and parallel to the dry elevated micro-sites a) that sloped down (~2%) to their parallel and adjacent former drainage ditches (studied by Montemayor et al., 2008); c) saline non-waterlogged (with a non-saline upslope) − occurred as pairs and were shaped approximately like a quarter of a circle that sloped down (~5%) from dry non-saline (not affected by the storm surge) to waterlogged areas b); d) very dry − elevated areas at the farthest end of each peat field from the service road; and e) non-waterlogged (with a saline upslope) − occurred in pairs and were similar in shape to micro-sites c). Micro-sites c) (plant experiments) and micro-sites b) (sand incubation experiment) were the experimental sites of this current paper. The total number of micro-sites c) was 32 (2 micro-sites × 16 parallel peat fields). Non-waterlogged areas are defined by moisture contents (% dry weight basis) ≤1000%, derived from Montemayor et al. (2008).

2.2. Experiment 1 − transplant of J. balticus

2.2.1. Collection of plant materials

J. balticus sods were collected from a nearby drained, sandy soil, non-saline marsh close to the study area that has been isolated from the sea by a service road. The intertwined network of roots and rhizomes packed the sandy soil tightly to a depth of about 12−13 cm; sods measuring 10 × 15 cm were collected on 6−9 June 2005.

2.2.2. Experimental design

Five micro-sites c) (replicates) were randomly selected from a total of 32. Three rows (fixed factor 1: Location) were laid across the slope of each micro-site at 2 m interval (Fig. 1). Starting from the wettest, Locations were designated as Bottom, Middle, and Top row. Ten individual sods were planted on each Location at 30 cm distance on the same day they were collected. The total number of sods was, 3 Locations × 10 sods × 5 replicates = 150. Plant parameters were measured at the end of the growing season of the year they were planted (Year 0; 12 August 2005) and repeated the following year (Year 1; 9 August 2006) (fixed factor 2: Time).

2.2.3. Plant parameters

The survival of individual plants per Location per replicate was counted and recorded as percentage. Three sods per Location per replicate were randomly selected to determine average height of stems, number of stems per sod, and the number of flowers per sod.

2.3. Experiment 2 − transplant of Spartina pectinata

2.3.1. Collection of plant materials

S. pectinata was collected from patches that colonized the non-saline and sandy sides of the service road. Two groups of plants were harvested: (i) plants with their sand substrate intact and (ii) plants with their sand substrate shaken-off and from which J-stem sections were prepared (NRCS, 2000), *i.e.*, a single plant was trimmed off about a third of the length of the leaves and the rhizome was trimmed off such that it formed a J-shape with the stem. Sods (or bowled plants) about 20 cm × 20 cm and 10−15 cm deep were collected 6−9 June 2005. Sods had to be handled gently as the rhizomes and roots held the sand substrate loosely.

2.3.2. Experimental design

S. pectinata was planted beside the J. balticus experiment (above) and followed the same fixed factor 1: Location (Section 2.2.2). However, the S. pectinata experiment had two Planting methods (fixed factor 2) laid side by side but 1 m apart: (i) With sand substrate and (ii) Bare root J-stem section as described above (Section

2.3.1) and by Montemayor et al. (2008). The With sand substrate method, had ten individual sods planted at each Location at 30 cm apart. The average number ± SE of stems per sod was: Bottom rows = 11.5 ± 1.3, Middle rows = 12.4 ± 1.5, and Top rows = 9.5 ± 1.2. The total number of sods was, 3 Locations × 10 sods × 5 replicates = 150. The Bare root stem section method had ten spots at each Location planted with three bare root J-stem sections per spot at 30 cm distance. The total number of planted spots was, 3 Locations × 10 spots × 5 replicates = 150. Planting was done on the same day plants were collected. Measurements were made at the end of the growing season of the year they were planted (Year 0; 12 August 2005) and repeated the following year (Year 1; 9 August 2006) (fixed factor 3: Time).

2.3.3. Plant parameters

Plant parameters were measured as per section 2.2.3, and the number of flowers was replaced with the ratio of number of flowers: number of stems. Using the ratio was a way to standardize both Planting methods and remove the effect of the pre-determined three stems per planting spot for the Bare root J-stem section method.

2.4. Experiment 3 − transplant of A. stolonifera

2.4.1. Collection of plant materials

Two hundred and forty individual mature plants of A. stolonifera with their intact sand substrate were collected in three batches on 26−28 June 2005. The plants were found growing as ruderals on the non-saline sandy yard of the abandoned peat processing building located near the study area. The numerous fine root hairs of the plants held their sand substrate very tightly packed to a depth of about 6−8 cm. Plant identification was verified through Tiner (1987) and the variety was *compacta* Hartm.

2.4.2. Experimental design

Eight micro-sites were randomly selected as replicates from the remaining 27 that were not planted to J. balticus and S. pectinata experiments. Planting was done following the Locations (fixed factor 1) in sections 2.2.2 and 2.3.2. Ten individuals were planted on each Location at 50 cm spacing on the same day they were collected. The total number of plants was 3 Locations × 10 plants × 8 replicates = 240. Plant parameters were measured at the end of the growing season of the year they were planted (Year 0; 12 August 2005) and repeated the following year (Year 1; 6 October 2006) (fixed factor 2: Time).

2.4.3. Plant parameters

Plant parameters were measured as per section 2.2.3. In addition, three plants per Location per replicate were randomly selected and minimum and maximum horizontal widths (cm) were measured. Horizontal widths were measured because these plants were prostrate or spreading in growth characteristic and the measurement of plant height (dominated by height of flowers) was considered inappropriate.

2.5. Characteristics of saline non-waterlogged micro-sites

2.5.1. Weather

An automated meteorological station (Campbell Instrument Inc.) recorded precipitation from a tipping bucket rain gauge every 20 min, as well as net radiation and ground heat flux. Total evaporation was calculated according to Priestly and Taylor (1972). More details are available in the studies of Montemayor et al. (2008) and Mouneimne and Price (2007).

2.5.2. Moisture content, electrical conductivity, and pH

Peat samples were collected from undisturbed spots of Top, Middle, and Bottom rows (fixed factor 1: Location) beside the experiments on 14 Jun, 5 Jul, 18 Jul, and 3 Aug (fixed factor 2: Time). A metal pipe of 6.1 cm diameter × 5 cm height was used as a core sampler. Samples were taken at Depths (fixed factor: 3) 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm. All samples were extruded immediately after extraction and stored in sealed plastic bags, stored in the refrigerator and analyzed within a week of collection. Two sets of samples were collected at each Location per replicate (total of 13 replicates; 5 for the *S. pectinata* and *J. balticus*, and 8 for the *A. stolonifera* experiments); one set was for moisture content (θ) determination, and the other was for determining electrical conductivity (EC) and pH.

Moisture content was determined gravimetrically by drying at 100 °C for 72 h and was subsequently calculated as g g^{-1} oven-dry weight basis (% g g^{-1} dwb) (Farnham and Finney, 1965; Rowell, 1994). For EC and pH, a sample was vacuum-filtered through Fisherbrand filter paper Qualitative P8-crepe, while simultaneously pressing the sample by hand using a glass jar. The filtrate was then measured for EC using YSI Model 33, S-C-T Meter (Yellow Springs instrument Co., Inc.) and pH using Fisher Scientific Accumet pH meter 10. EC of some filtrates that exceeded the maximum reading of the measuring instrument were diluted and corrected back to the original θ; pH was measured on the filtrates.

2.5.3. Depth of water table

Pairs of wells were installed along a slope, such that each pair has one in a Top row and the other in a Bottom row Location and both were installed 50 cm away from plant rows. All the five replicates of the *J. balticus* (Section 2.2) and *S. pectinata* (Section 2.3) experiments had 5 pairs of wells installed in the middle of the 100 cm width dividing space between these two experiments. In the *A. stolonifera* experiment (Section 2.4), only five out of eight replicates had a pair of wells installed along the slope in the middle of the planted rows. The wells were made of 2.5 cm diameter PVC pipes, 100 cm length and perforated throughout its length at 3.8% porosity. Each well was lined with fine nylon netting on its outer side before installation to prevent peat particles from entering them. The depth of water table (WT) was measured approximately every week between 14 June and 12 August 2005. The average of the measurements from ten wells or less (when some were still frozen) was calculated for each Location (Top and Bottom rows) on each date.

2.5.4. Capillary fringe

On 9 July 2005, a pit measuring 1 × 1 m wide was dug to a depth of 1 m that reached the bottom of the peat profile (sand), in the Top row of one of the saline non-waterlogged micro-sites that was free from any experiment. Core samples were taken from one face of the pit in 5 cm increments starting from the surface down to the WT, on 9 July and 6 August. The pit was kept covered with a plywood sheet between these dates, and five cm of peat was scraped off the pit face before sampling. Methods of core sampling, samples processing and analysis for θ, EC, and pH were the same as in Section 2.5.2. The capillary fringe (CF), a saturated zone above the WT where water is retained by capillary forces (Hornberger et al., 1998) was estimated from the θ profiles (Ronen et al., 1997).

2.6. Experiment 4 – sandy soil volume incubation

2.6.1. Collection of sandy soil volumes

Seventy-two cylindrical volumes (9.7 cm diameter and 13.3 cm height) of dry sandy soil containing dormant *J. balticus* roots and rhizomes were collected using a steel pipe with a cutting edge on one end, from a drained non-saline marsh near the study area on 21–22 May 2005.

2.6.2. Experimental design

This experiment was done on the uppermost elevation (least waterlogged) areas of four randomly selected saline waterlogged micro-sites b). This study was originally intended to complement the earlier study on micro-sites b) (Montemayor et al., 2008) but the predominant effect of waterlogging on plants precluded the thought on the effects of sand itself as a substrate. The purpose of this experiment was to determine what would be the changes in θ, EC, and pH of a sandy soil volume when incubated in saline and waterlogged peat fields for a period until the EC of the sandy soil volume equaled that of the surrounding peat. Three cylindrical soil volumes were placed for each of the incubation duration (fixed factor 1: Incubation time) of: 1, 3, 5, 10 and 20 days. The total number of soil volumes incubated was 3 sandy soil volumes × 5 Incubation times × 4 replicates = 60 soil volumes. Twelve soil volumes were used for Control treatment (0 day incubation) making a total of 72 sandy soil volumes. Soil volumes were placed into holes scooped by hand in the peat fields at 50 cm spacing in such a manner that the top surfaces of the soil volumes were flush with the peat field surface. Soil volumes were placed on 23 May 2005 (0 day incubation), a day after they were collected. Soil volumes were processed (see the next Section 2.6.3) to determine changes in peat characteristics in the annular Outer and Inner sections of each soil volume (fixed factor 2: Sod sections).

At 0 day incubation and during each of the subsequent incubation periods, 3 cylindrical volumes of peat of the same size as the sandy soil volumes per replicate were sampled 25 cm away from the rows of incubated sandy soil volume. The total number was 3 peat volumes × 6 Incubation times × 4 replicates = 72.

Additional 3 cylindrical volumes of sandy soil and another 3 cylindrical volumes of peat were taken to the laboratory for determination of particle size distribution, organic matter content (% Loss on Ignition), dry bulk density (g cm^{-3}), particle density (g cm^{-3}), and total porosity (%).

2.6.3. Sandy soil volume characteristics

Each cylindrical soil volume was divided into two Sod sections. A 1.5 cm thick soil was trimmed off the outer and bottom section of cylindrical soil volumes using a sharp stainless steel knife which constituted the Outer section. The remaining section of the soil volume was the Inner section. The Outer and Inner sections were processed separately. Plant parts (surface litter, roots and rhizomes) were removed from the soil. The Outer sections of three soil volumes for each incubation period were combined as a composite sample, stored in a sealed plastic bag and refrigerated until the next processing step, a week later. The same process was applied to the Inner sections.

Three sub-samples were taken from each composite sample of a replicate per Incubation time, to make a 1:2 saturation extracts using deionized water (ICARDA, 2001). These were allowed to stand for 12 h and then filtered by gravity through No. 42 Whatman ashless filter paper. Filtrates were tested for EC and pH as described in Section 2.5.2.

Another three sub-samples from each composite sample of a replicate per Incubation time were taken for gravimetric determination of θ as described in Section 2.5.2. The average of the 3 sub-samples of a replicate per Incubation time, and Control for θ, EC, and pH was the value used for statistical analysis.

2.6.4. Peat characteristics

Three peat volumes per replicate per incubation period, as well as for the control treatment, were mixed to make a composite

sample, stored in a sealed plastic bag and refrigerated until the next processing step, a week later. From each composite sample, three ~200 g sub-samples were taken for gravimetric determination of θ by the method described in the Section 2.5.2. The rest of the composite sample was processed to determine EC and pH using the method described in the Section 2.5.2. The average of the 3 sub-samples of a replicate per Incubation time, and Control for θ, EC, and pH was the value used for statistical analysis.

Organic matter content was determined by loss-on-ignition in a muffle furnace for 4 h at 550 °C (Rowell, 1994). Particle size distribution was determined by hydrometer method (Gee and Bauder, 1986). Von Post scale of humification (H1 to H10) was used to characterize the state of peat decomposition (*e.g.* Malterer et al., 1992; Carter and Gregorich, 2007). Dry bulk density was determined by obtaining the mass of a known volume of peat or sandy soil after oven-drying at 105 °C. Particle density was determined by measuring the volume of a known mass of peat or sandy soil that had been air-dried for a month and oven-dried at 90 °C for 24 h (Munro, 1982). The procedure by Rowell (1994) was modified by dispersing in 50–60 ml toluene, 2–3 g peat or 5–6 g sod soil, allowed to stand covered overnight and subsequently topped up to 100 ml in a volumetric flask. Total porosity was calculated as porosity = 1 − (bulk density/particle density).

2.7. Statistical analysis

Most of the data sets for plant parameters could not qualify as normal distributions and were mostly treated to Rank transformation. Plant parameters were analyzed using General Linear Model Repeated Measures ANOVA of transformed data applying the approach of Conover and Iman (1981). Data were analyzed using IBM SPSS v. 20, IBM Corp., Armonk, New York.

Sandy soil volume parameters θ, EC and pH for Inner and Outer sections were analyzed using a two-way ANOVA. Tests for normality (K-S Test; Lilliefors) and homogeneity of variances (Levene's Test) were performed failing which, data were transformed, mostly as Rank. Analyses were done using SYSTAT 13, Systat Software Inc., Chicago, Illinois.

3. Results

3.1. Experiment 1 − transplant of J. balticus

The survival of *J. balticus* was excellent in all Locations at the end of the first year's growing season and after a year of growth (Fig. 2, Table 1). After a year, there was a significant increase in the number of flowers and number of stems per sod. However, there was no significant difference in any of the plant parameters due to Location. A notable phenomenon about this experiment was the unexpected growth of *Festuca rubra*, inside the sods and it appeared more dominant than *J. balticus*. No data was collected for *F. rubra* as it did not have a Year 0 data.

Fig. 2. *J. balticus* Survival (%), Number of flowers per sod, Number of stems per sod, and Plant height (cm), ±SE, at three Locations during Year 0 and Year 1.

3.2. Experiment 2 − transplant of S. pectinata

Survival was significantly higher for those planted With sand substrate compared with those planted as Bare root J-stem sections (Fig. 3, Table 2). Plants grown With sand substrate had significantly more number of stems per sod and were taller than those planted as Bare root J-stem sections. However, these responses were influenced by the effect of a year of growth and the favorable

Table 1
Two-way Analysis of variance for the *J. balticus* experiment.

Plant parameters	Fixed factors							
	Time				Location			
	df	MS	F	P	df	MS	F	P
Survival (%)	1	270.0	2.0	0.183	2	67.5	0.5	0.619
No. of flowers per sod	1	12,759.7	124.0	**0.000**	2	82.9	0.090	0.434
No. of stems per sod	1	6412.3	35.3	**0.000**	2	277.2	277.2	0.330
Plant height (cm)	1	10.8	0.143	0.712	2	122.3	2.076	0.168

Note: The interaction between Time and Location factors was not significant ($P \leq 0.05$) for all plant parameters. Bold fonts indicate significant difference at $P < 0.05$.

conditions of Bottom rows (Time × Location interaction). The number of stems per sod or planting spot significantly increased but the number of leaves per stem decreased, after a year of growth. Bottom rows were favorable for increased number of leaves and flowers. A notable visual observation was the chlorotic (yellowish) appearance of leaves of those planted as Bare root J-stem sections.

3.3. Experiment 3 — transplant of A. stolonifera

After a year of growth, survival and widths significantly decreased (Fig. 4, Table 3). However, this trend was reversed with a significant increase in the number of flowers per plant. There was no effect of Location on any of the parameters.

3.4. Characteristics of saline non-waterlogged micro-sites

3.4.1. Precipitation
There were 33 rainfall events from 3 May to 15 August which totaled 212 mm. Most of the rainfall (139.3 mm) occurred before 21 June or during the pre-thaw period (of the frozen peat layer beneath the surface; see Section 3.4.3); between 21 June and 19 July, there was only 16 mm, and between 19 July and 15 August, 55.8 mm. The total evaporation was estimated to be 311 mm, ~100 mm greater than precipitation. Details on meteorological conditions are found in Montemayor et al., 2008.

3.4.2. Electrical conductivity, moisture content, and pH
Both EC and θ values showed the same trend; both of increasing values downslope, from Top, Middle, and to Bottom rows (Fig. 6). Moisture content decreased in all Locations with the advance of the season while EC, in contrast, increased. Notable differences with Depth were observed with EC, the highest values were found on the top surface, 0—5 cm as the season advanced. In June, EC increased with Depth and the trend was reversed by July with increasing values at all Depths as the season advanced. pH decreased with increasing EC; the relationship was a power equation, $pH = 3.5301EC^{-0.089}$ ($R^2 = 0.68$).

3.4.3. Depth of water table
All wells were still frozen until June 9th and some wells in the Top rows remained frozen or partially frozen until late July. All wells in the Bottom rows were thawed by 8 July and in Top rows by 6 August. Bottom rows maintained a much higher WT compared to the Top rows (Fig. 6) throughout the study period. The WT before the thaw of the frozen layer (pre-thaw period) was perched (Montemayor et al., 2008) and the actual WT depths were those measured at and after the thaw of the frozen layer (post-thaw period). For most measurements this was after 8 July. On 8 July the depth of the WT for Bottom rows was at ~35 cm while in Top rows was at ~60 cm. Depth of the WT decreased further as the season advanced.

3.4.4. Capillary fringe
The CF was estimated from the two moisture profiles to be 40—50 cm above the WT (Fig. 7). The peat profile consisted of different plant origins; pine wood and shrubs at the very bottom, *Sphagnum* and sedge peat above it, and *Sphagnum* peat at the surface. The differences in plant origin might have influenced the range of saturated θ. For example, at this site, wood peat (at the bottom) had less 'theta' than *Sphagnum* peat at 50 cm depth.

3.5. Experiment 4 — sandy soil volume incubation

The sandy soil volume particle size distribution consisted of 87.3% sand, 12.7% silt, and 0% clay. The thickness of the soil horizons
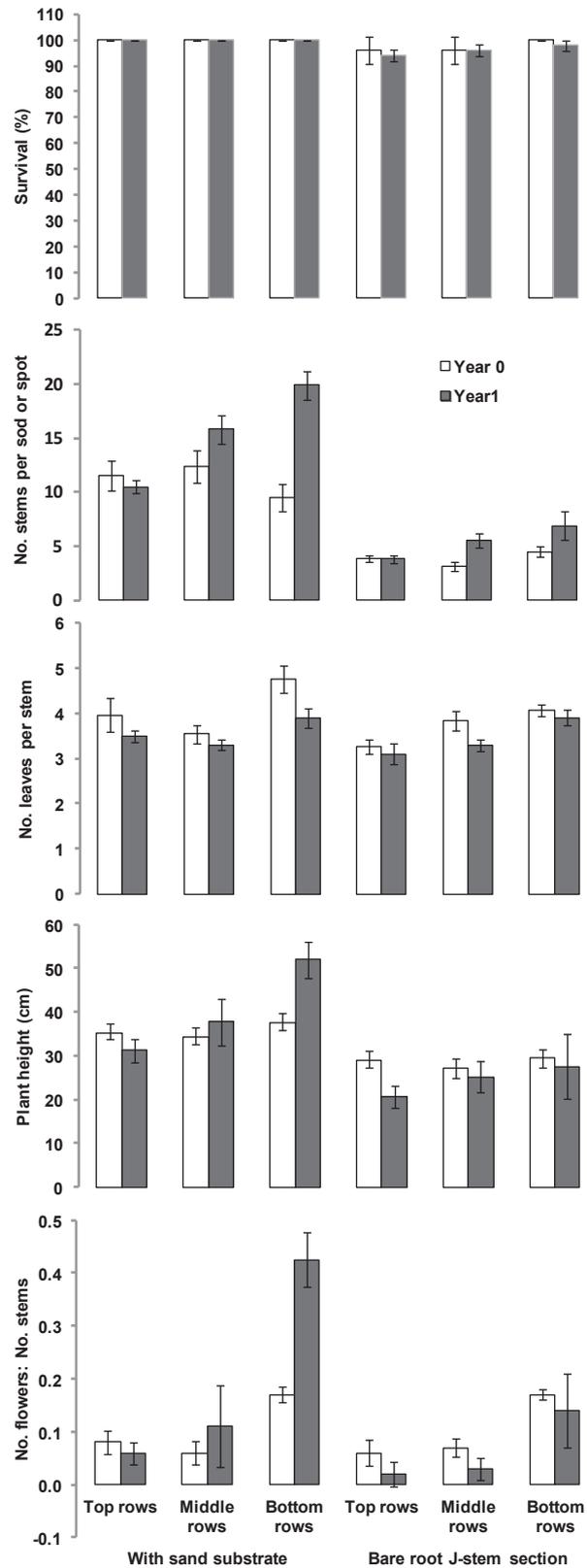
Fig. 3. *S. pectinata* Survival (%), Number of flowers per sod or planted spot, Number of stems per sod or planted spot, Number of leaves per stem, and Plant height (cm), ±SE, in Year 0 and Year 1, for both Planting methods: With sand substrate and Bare root J-stem sections.

Table 2
Three-way analysis of variance for the *S. pectinata* experiment.

Plant parameters	Fixed factors															
	Time				Location				Planting method				Time × location			
	df	MS	F	P	df	MS	F	P	df	MS	F	P	df	MS	F	P
Survival (%)	1	135.0	2.00	0.170	2	438.8	1.083	0.354	1	3375.0	8.333	**0.008**				
No. of stems per sod or spot	1	1848.2	19.95	**0.000**	2	282.3	2.641	0.092	1	9525.6	89.13	**0.000**	2	375.5	4.053	**0.030**
No. of leaves per stem	1	904.8	5.417	**0.029**	2	2750.7	13.29	**0.000**	1	522.2	2.52	0.125				
Plant height (cm)	1	299.3	3.36	0.079	2	382.2	2.82	0.080	1	6955.3	28.73	**0.000**	2	333.2	3.744	**0.038**
Ratio no. of flowers: No. of stems per sod or spot	1	166.7	1.477	0.236	2	3243.4	11.51	**0.000**	1	640.3	2.274	0.145				

Note: All other interactions between fixed factors were not significant at P ≤ 0.05. Bold figures indicate significant difference (P < 0.05).
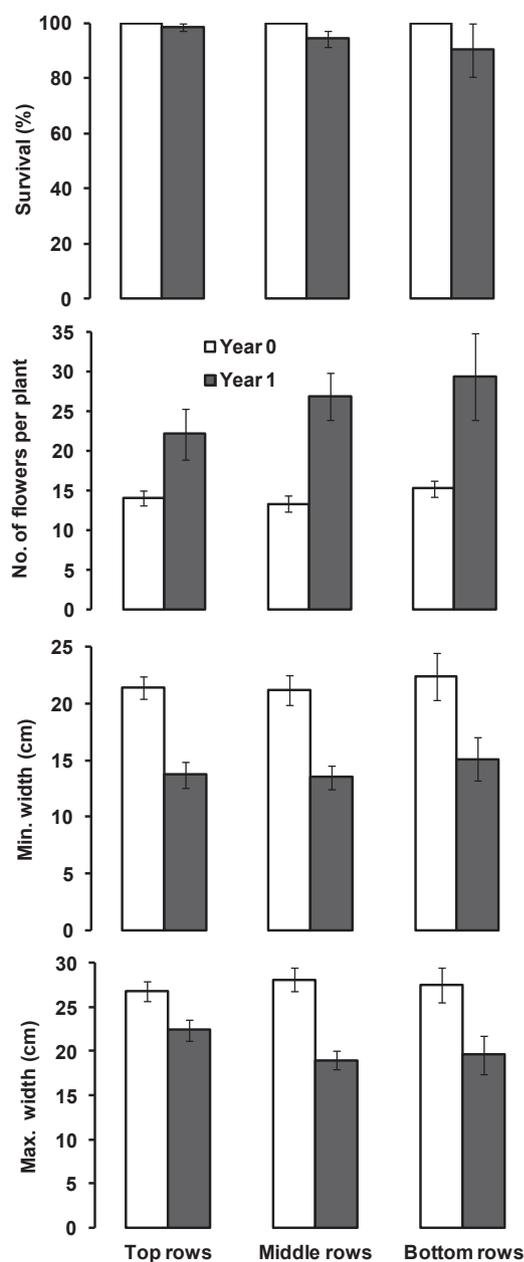
Fig. 4. *A. stolonifera* Survival (%), Number of flowers per plant, Minimum width of plant spread (cm), and Maximum width of plant spread (cm), ±SE, in Year 0 and Year 1.

were: 3.5 cm O-horizon and 8.9 cm Am horizon. The dry bulk density was 0.82 g cm^{-3} ($\pm$0.09 SD), particle density of 2.25 cm^{-3} ($\pm$0.03 SD), and a total porosity of 0.64. Peat had 93.4% ($\pm$2.13 SD)

organic matter content, a dry bulk density of 0.073 ($\pm$0.009 SD), particle density of 1.38 ($\pm$0.13 SD), total porosity of 0.95, and Von Post humification scale of H3 (very slightly decomposed) to H5 (moderately decomposed).

EC of the sandy soil volume increased significantly with increasing Incubation time, and the EC of sandy soil approached that of peat at 3–5 days of Incubation time (Fig. 8).

The sandy soil volume pH changed significantly with Incubation time, from a pH of near 6 to less than this value but above pH 5 beginning day 1 to day 20 (Fig. 8). The pH of the surrounding peat was much lower at ~3.5 throughout the study period. There was no significant difference between Outer and Inner sections of the sandy soil volume and there was no significant interaction between factors (Incubation time × Sod section) for both EC and pH (Table 4).

The θ of the sandy soil volume significantly increased (Table 4) beginning day 1 and remained somewhat constant thereafter for both Outer and Inner sections. The Inner section had significantly higher θ than the Outer section. There was no significant interaction between factors (Incubation time × Sod section). The increase of θ during the last half of the incubation period was due two rains on the 5th (20.0 mm) and 10th (8.0 mm) day of Incubation time.

4. Discussion

Increasing the pH of plant substrate by the application of sand is a potential method to increase the number of species to revegetate saline non-waterlogged peat fields. This was substantiated by the sand volume incubation experiment where its pH remained much higher than the surrounding peat. Although the incubation period was short, this hypothesis could be substantiated by favorable plant responses after a year of growth: the unexpected growth of the *F. rubra* in the *J. balticus* sods, the responses of *A. stolonifera* by curling up its stolons and its luxuriant flowering, and the excellent survival and growth of *S. pectinata* when planted with its sand substrate especially in Bottom rows Location. The excellent survival of *J. balticus* in all Locations and *S. pectinata* in Bottom rows reaffirm the findings of our earlier study (Montemayor et al., 2008) that *J. balticus* is intolerant of prolonged waterlogging while *S. pectinata* requires constant waterlogged conditions in saline conditions.

The excellent survival (98%) and growth of *J. balticus* (significant increase in the number of flowers and stems after a year of growth) in all Locations demonstrated that this species grows well in areas that are moist and not subject to prolonged waterlogging (Fig. 2). This confirms the findings of our earlier study (Montemayor et al., 2008) in which *J. balticus* showed just a fair survival (68.5%) in the relatively driest Location of saline waterlogged micro-sites (Montemayor et al., 2008). The Bottom rows in this current paper were flooded ($\geq$1000% moisture content dwb) until 14 June (Fig. 5), whereas in saline waterlogged areas of the previous study, the relatively driest Location (Up-areas) was flooded for a longer duration, until 26 June (Montemayor et al., 2008), i.e., 12 days

Table 3
Two-way analysis of variance for the *A. stolonifera* experiment.

Plant parameters	Fixed factors							
	Time				Location			
	df	MS	F	P	df	MS	F	P
Survival (%)	1	300.0	5.979	**0.023**	2	45.2	0.901	0.421
No. of flowers per plant	1	17.08	22.4	**0.000**	2	0.376	0.319	0.730
Minimum width (cm)	1	686.07	57.29	**0.000**	2	9.053	0.319	0.681
Maximum width (cm)	1	608.16	40.55	**0.000**	2	5.537	0.224	0.801

Note: The interaction between Time and Location factors was not significant ($P \leq 0.05$) for all plant parameters. Bold figures indicate significant difference (P < 0.05).
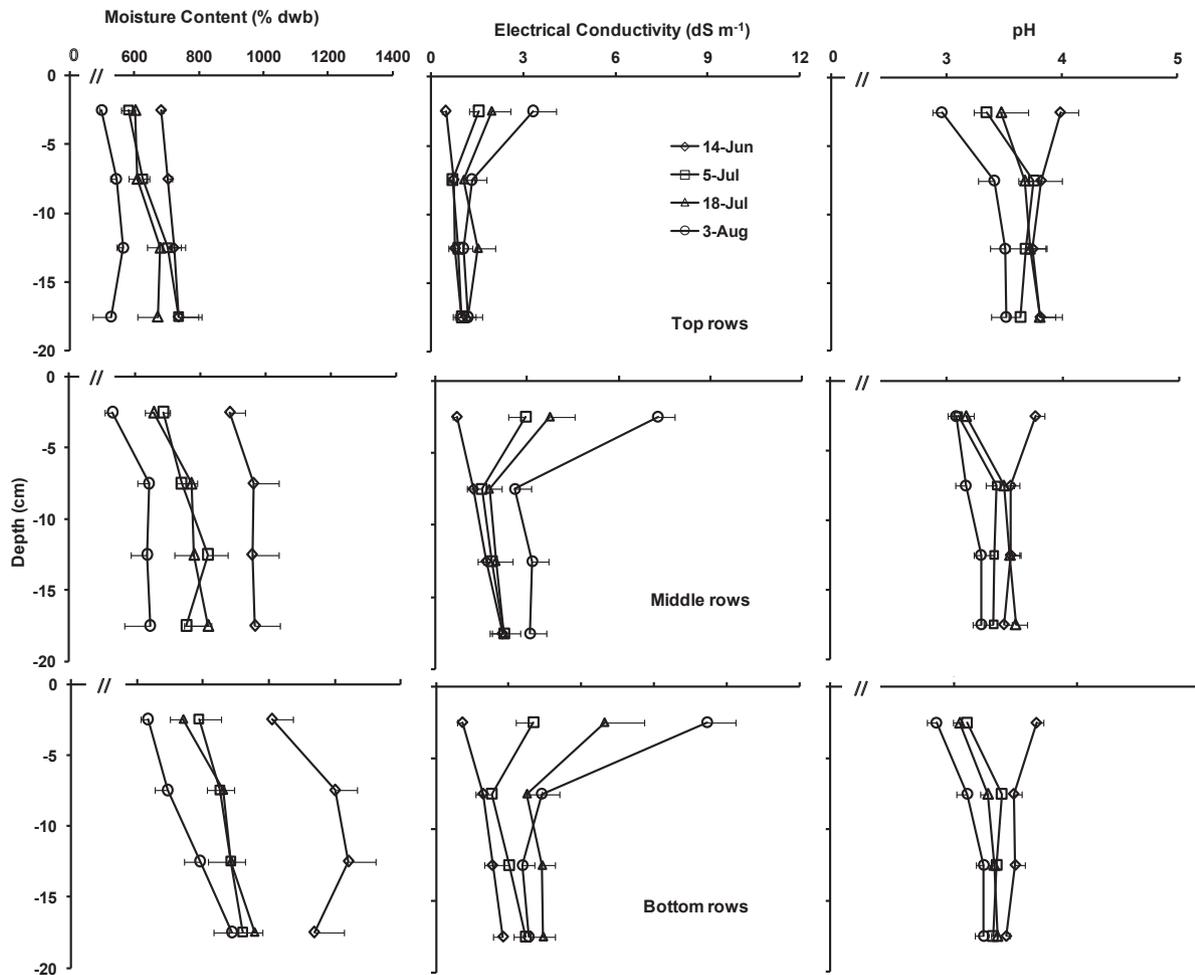
Fig. 5. Moisture content (% dwb), Electrical conductivity (dS cm^{-1}), and pH + or − SE (to avoid overcrowding), of peat at Depths 0–5, 5–10, 10–15 and 15–20 cm at three different Locations in the saline non-waterlogged micro-sites at four different periods during the duration of the plant experiments.

longer. An unexpected result in this current paper was the luxuriant growth and flowering of *F. rubra* within the *J. balticus* sods, whereas in the donor marsh site, it was growing inconspicuously beneath the dense growth of *J. balticus*. Perhaps, in addition to the suitable sand substrate conditions, the open spaces between plants (30 cm) and between rows (100 cm) must have provided a suitable growth environment for *F. rubra*. It is unlikely that the reduction of sand substrate pH by about half a unit (Fig. 8) could have been the reason allowing *F. rubra* to be competitive with *J. balticus*.

The advantageous effect of With intact sandy substrate method was demonstrated by 100% survival, and better growth (greater number of stems produced and plant height development) of *S. pectinata* after one year of growth compared with Bare root J-

stem section method used in our earlier study in saline waterlogged areas (Montemayor et al., 2008) (Fig. 3). The Bottom rows were more favorable for growth and reproduction which were demonstrated by the greater number of leaves per stem and the number of flowers per stem compared with the other Locations. The superior growth in Bottom rows attests to the known characteristic of *Spartina* species of managing sodium by secreting it through salt glands found on the leaves, via the transpiration stream (Rozema et al., 1981; Bradley and Morris, 1991; Vasquez et al., 2006). Hence, as was observed in the sources of plant materials (dry non-saline sandy roadsides) for this currently reported experiment, *S. pectinata* can grow well in drier soils so long as it is non-saline; where the soil is saline, the habitat must have sufficient and
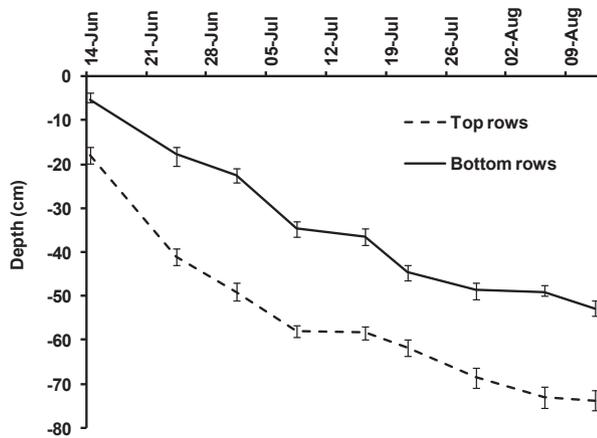
Fig. 6. Average depth of water table (cm) ± SE in Top rows and Bottom rows during the growing period of Year 0.
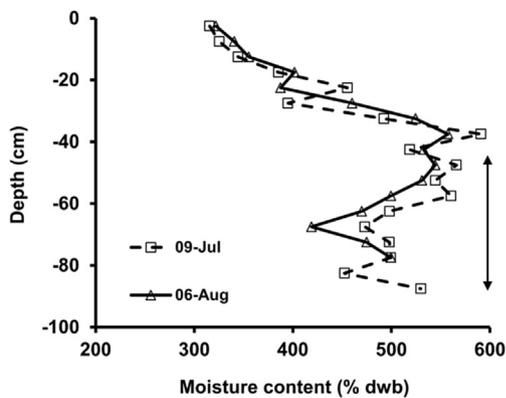
Fig. 7. The capillary fringe (double-headed arrow) was estimated from two measurements of moisture content profile.

Fig. 8. Moisture content (% dwb) with different scales for sandy soil volume and peat, Electrical conductivity (dS cm^{-1}), and pH + or − SE (to avoid overcrowding) of sandy soil and waterlogged peat.

constant water supply (as in salt marshes) to enable *S. pectinata* to excrete salts (Tester and Davenport, 2003). The chlorotic appearance of leaves of those planted as Bare root J-stem sections could be the result of a combination of stresses from lack of water to excrete salts and the lack of benefit from a sandy substrate with intact developed roots. Therefore, Bare root J-stem section method is not suitable in saline non-waterlogged areas of peat fields. The growth response of *A. stolonifera* by curling up its stolons and avoiding contact with the surrounding peat seemed to indicate its intolerance to the very acidic condition of the surrounding peat, from pH 3 to 4. In its natural habitat, stolons lie flat on the soil surface, which was the case when they were newly transplanted. The luxuriant flowering was a characteristic not observed in the donor site. It seemed that under the constraint in vegetative growth, the plant's resources were directed towards reproductive growth.

The moisture source for plant growth during the pre-thaw period was from precipitation and most of it was received during this period. The WT dropped to below 30 cm from the surface, well below the root zone, during the post-thaw period (July) (Fig. 6), a critical period when plants begin rapid growth. However, the rise of the capillary fringe of ~40–50 cm (Fig. 7) was mostly likely able to supply moisture to the plants and kept the micro-site moist during the post-thaw period. There could also be a potential horizontal seepage from the adjacent waterlogged micro-sites but this was not determined in this study. The delay in thaw of the frozen layer in Top rows for up to a month compared with Bottom rows showed the insulation characteristics of drier *in-situ* peat. The higher saturated θ
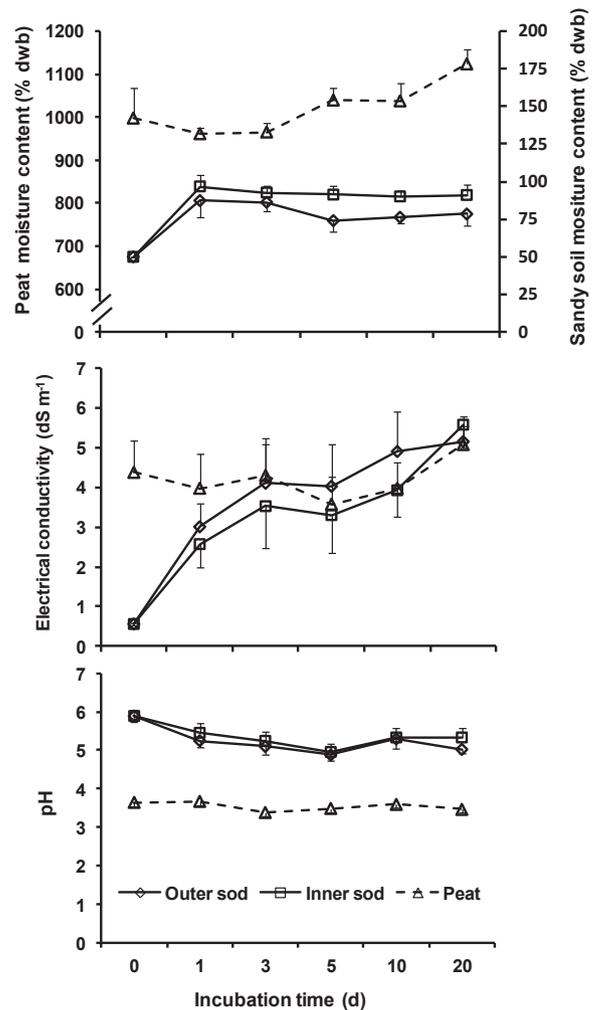
of *Sphagnum* peat compared with that of wood peat was another notable characteristic. Since *Sphagnum* peat was the dominant material, this characteristic probably influenced capillary rise and the availability of moisture to plants during the post-thaw period.

EC and θ increased downslope (Fig. 5) which was a pattern different from those saline waterlogged micro-sites described in an earlier study on the same study area (Montemayor et al., 2008), where salinity decreased with increasing moisture content downslope. This difference demonstrates that these were indeed two distinct groups of micro-sites within each of the remnant peat fields. The temporal variations in EC were the same with the previous study (Montemayor et al., 2008); that of increasing EC with decreasing θ as the season progressed. Similarly, the pre- and post thaw periods were clearly distinguishable. During the pre-thaw period EC increased with Depth of peat and this trend was completely reversed during the post-thaw period, notably with the top-most 0–5 cm surface with the highest salinity. As was found in our previous study, the pH of peat decreased as EC increased with the advance of the season. This implies that stresses to plant growth, acidity and salinity, were both exacerbated with the advance of the season.

These plant experiments were originally not designed to

Table 4
Two-way ANOVA for the sandy soil volume incubated in saline and waterlogged peat fields experiment.

Soil parameters	Fixed factors							
	Incubation time				Sod-section			
	df	MS	F	P	df	MS	F	P
Electrical conductivity (dS cm^{-1})	5	1075	10.88	**0.000**	1	136.7	1.384	0.247
pH	5	650.4	4.45	**0.000**	1	117.1	0.802	0.377
Moisture content (% dwb)	5	1667	10.27	**0.000**	1	1159	7.137	**0.011**

Bold figures indicate significant difference ($P < 0.05$).

specifically determine the effect of sand on pH. The observed plant responses from three experiments together with the results of the sandy soil volume incubation experiment (Fig. 8) suggest that spreading a sand layer on the surface of peat will allow the establishment of some salt marsh grasses, e.g. *A. stolonifera* and *F. rubra* in addition to *J. balticus* and possibly other salt marsh species, on the saline non-waterlogged micro-sites. This approach does not return the disturbed area to its original *Sphagnum*-dominated peat-accumulating peatland but to another type of wetland dominated by salt-marsh vegetation. Transforming barren peat fields into a new wetland will restore some ecological functions such a habitat for wildlife, enhancement of biodiversity, and provision of connectivity between the adjacent intact natural areas fragmented by peat extraction. Spreading a layer of sand over peat will be similar to the creation of a salt marsh above an existing peatland. The development of salt marshes on top of peat as natural ecosystems exists in many parts of the world, e.g. in the United States (Bloom, 1964; Redfield and Rubin, 1962), Ireland (Cott et al., 2012), and northwestern Europe (Allen, 2000). Our set of studies provides some explanation to the development of such ecosystems. Therefore, with this natural pattern of ecosystem development serving as a model, the spreading of a sand layer on the surface can potentially be a revegetation technique for saline non-waterlogged peat fields.

For future studies, it would be useful to determine the duration of the maintenance of higher pH for a given thickness of sand applied on the surface of peat and its effect on the vertical movement of salt, and subsequently on plant community composition. There is also the possibility that an established vegetation cover may have an effect on ground surface evaporation and consequently affect the vertical movement of salts.

In addition to New Brunswick Canada, our set of studies are relevant to the reclamation of the oil sands region in northern Alberta, Canada (Trites and Bayley, 2009) where mining exposes buried saline deposits (prairie evaporites). Bogs occupy extensive areas in the northern hemisphere (50°N—70°N) and historically have been drained and/or mined for fuel, forestry, and agriculture (Moore, 2000). Our studies are relevant to other places where bog restoration activities occur but may be beset by hydrological and ecological constraints, e.g., northern Europe (Vasander et al., 2003; Money and Wheeler, 1999), and the Great Lakes (Wilcox and Whillans, 1999) and the understanding and management of road salt impacted bogs (Wilcox and Andrus, 1987). As we found in our studies, bog restoration may take a different immediate trajectory than the re-establishment of the original bog species. These results are also useful for the understanding and management of vegetation in stormwater management ponds (NAS, 2009). Climate change and predicted sea level rise may find the results of our studies useful for proactive management of coastal bogs. In the larger context of restoration or reclamation of disturbed lands, we stress the recognition of plant species niches to minimize earth-moving activities and the manipulation of pH to suit plant requirements.

5. Conclusion

This study demonstrated the importance of substrate or soil pH as one of the determining factors in the successful revegetation or reclamation of disturbed and contaminated peatlands that can be extended to other disturbed wetlands or lands. It also showed that micro-topography of a disturbed landscape could generate distinct micro-sites or niches characterized by different spatial and temporal patterns of moisture and contaminant concentrations and their association with pH. Consequently, different micro-sites would be suitable to different species having different tolerance to stresses caused by the combined effect of pH, moisture levels, and contaminant concentrations throughout the growing season. The use of sand to provide a favorable pH suitable for salt marsh plant species to grow, is a potential revegetation technique for peatlands, especially where sand is readily available. Putting together the key findings of this current study and our previous studies on this study area, we conclude that the revegetation of the salt contaminated peat fields can be done using two methods based on the moisture characteristics of micro-sites: (a) waterlogged areas — directly plant *S. pectinata* (with or without sand substrate), and (b) non-waterlogged areas — apply a layer of sand and plant *J. balticus*, *F. rubra*, and *A. stolonifera*. The approaches in these studies are not confined in application to disturbed bogs but are also applicable to other types of land disturbance that require revegetation.

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